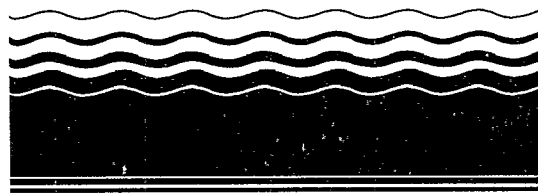




SITE

**SUPERFUND INNOVATIVE
TECHNOLOGY EVALUATION**



Technology Demonstration Summary

Hydraulic Fracturing Technology

Two pilot-scale demonstrations of the hydraulic fracturing technology for enhancing the permeability of contaminated silty clays have been evaluated under the Superfund Innovative Technology Evaluation (SITE) Program. The technology was jointly developed by the University of Cincinnati (UC) and the U. S. Environmental Protection Agency's (EPA's) Risk Reduction Engineering Laboratory (RREL). Tests were also conducted at UC Center Hill Solid and Hazardous Waste Research Facility (Center Hill Facility) by UC. These tests were conducted to determine the factors affecting soil vapor flow through sand-filled hydraulic fractures.

The hydraulic fracturing technology was demonstrated in 1991 and 1992 at a Xerox Corporation soil vapor extraction (SVE) site in Oak Brook, IL (the Xerox Oak Brook site), and at a bioremediation site near Dayton, OH (the Dayton site). The sites were contaminated with volatile organic compounds, and the *in-situ* permeability of onsite soils was less than 10^{-7} centimeters per second. The technology created multiple, sand-filled hydraulic fractures at depths of up to 15 feet below ground

surface (ft bgs). At the Xerox Oak Brook site, these fractures increased vapor flow by one order of magnitude in an area 30 times greater than the area affected by wells in unfractured soil. At the Dayton site, the groundwater flow rate was 25 to 40 times higher in a well screened in the fractured soil than in one screened in unfractured soil.

This Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the SITE demonstration that is fully documented in two reports under one cover (see ordering information at back).

Introduction

In response to the Superfund Amendments and Reauthorization Act of 1986, EPA established a formal program to accelerate the development, demonstration, and use of new or innovative technologies that offer permanent, long-term cleanup solutions at Superfund sites. This SITE program is administered by EPA's Office of Research and Development, RREL. One component of the SITE program is the demonstration program, which develops reliable performance and cost information



on innovative technologies so that potential users can assess a technology's suitability for specific site cleanups. During the demonstrations, hydraulic fractures were created to increase the *in-situ* permeability of contaminated soil. This permeability enhancement significantly improved the rates of vapor and water flow through the soil near the fractured wells.

Technology Description

The hydraulic fracturing technology is designed to create sand-filled fractures up to 1-in. thick and about 20 ft in radius in low permeability soils. These fractures, when created at several depths from 5 to 40 ft bgs, increase the permeability of contaminated soil. This increased permeability promotes the flow of vapors and liquid through the soil and enhances the effectiveness of SVE, bioremediation, and pump-and-treat remediation techniques.

The hydraulic fracturing equipment consists of a fracturing lance, a tool to create the initial notch, a continuous slurry mixer, and a positive displacement pump mounted on a trailer. A typical sequence of operations for creating hydraulic fractures is shown in Figure 1, and the slurry

mixer and trailer-mounted pump assembly is shown in Figure 2.

A borehole is drilled using 6 or 8-in. outside diameter, hollow-stem augers. Individual segments of the rod and casing are 5 ft long and are threaded together as required by fracture depth. The tip of the fracturing lance is then driven to a depth where a fracture is to be created. The lance is removed, leaving soil exposed at the bottom of the casing (see Figure 1). Steel tubing with a narrow orifice at one end (the notching tool) is inserted into the casing, and water is pumped through the tubing to create a high-pressure water jet. The water jet, which has a pressure of about 3,500 pounds per square inch, is rotated within the borehole and produces a disc-shaped notch extending 4 to 6 in. from the borehole (see Figure 1).

Sand slurry is then pumped into the notch to create a hydraulic fracture. Sand slurry is produced by mixing one part of granular solid (coarse sand proppant) with two parts of viscous fluid in a continuous mixer. The viscous fluid consists of a mixture of guar gum gel, water, and an enzyme that breaks down the gel after the

proppant has been deposited into the fracture. A hydraulic fracture is created by pumping a predetermined volume of slurry at rates of 10 to 25 gals/min into the notch. Lateral pressure from the soil on the outer wall of the casing effectively seals the casing and prevents leakage of the slurry. The fracture nucleates at the notch and grows radially up to about 20 ft from the borehole wall.

The gel-to-sand ratio in the slurry is adjusted to propagate the fracture and to move the sand into the fracture. The amount of the gel is reduced when a possibility exists of the fracture venting to the surface. In cases where the fracture propagates horizontally, the sand content is increased during pumping to increase the thickness and length of the fracture. The gel-to-sand ratio in the slurry is adjusted from fracture to fracture, depending on depth and site-specific soil conditions. For a fracture created at 15 ft bgs, about 150 gal of gel and 14 cu ft of sand are used.

The direction and distance of propagation of the fracture is measured by monitoring the uplift of the ground surface. Several stakes are placed along radial

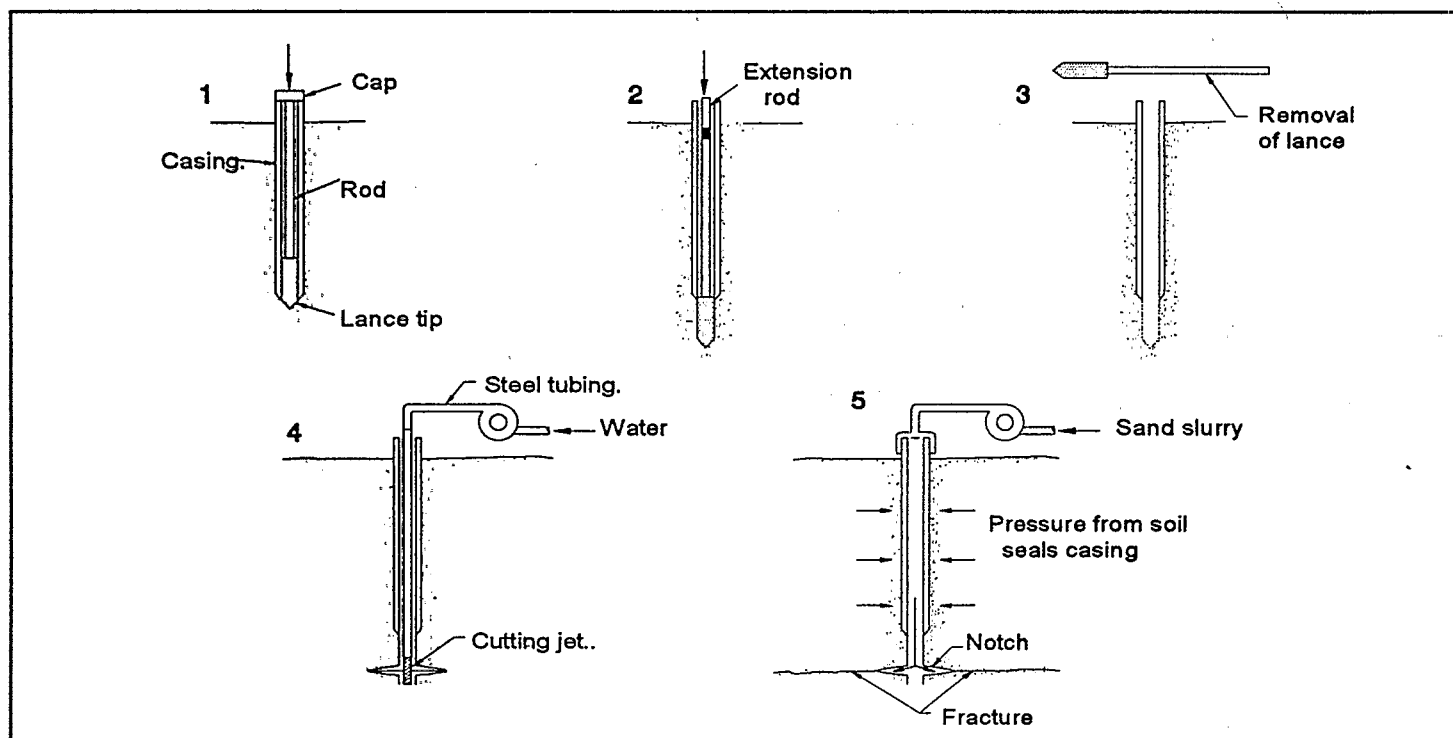


Figure 1. Sequence of operations for creating hydraulic fractures.

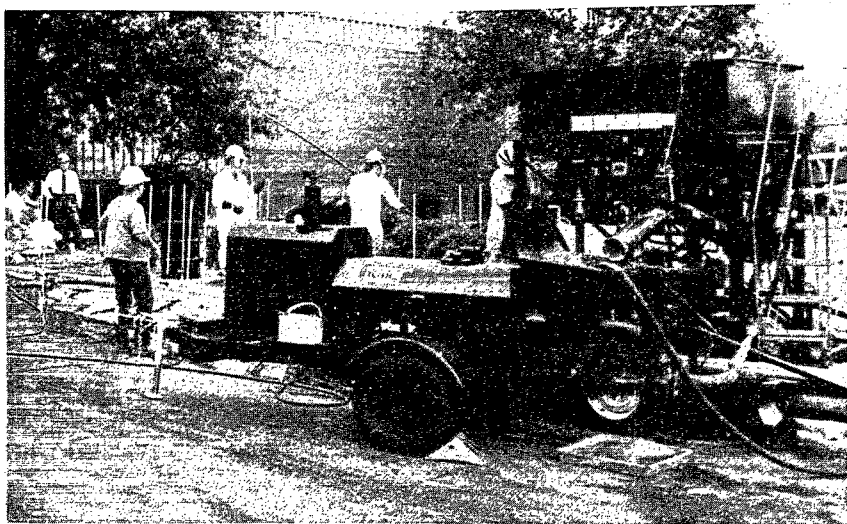


Figure 2. Slurry mixing and pumping equipment mounted on trailers.

directions around the borehole before fracturing. After fracturing, a leveling telescope can be used to measure the change in elevation of preexisting marks on the stakes to determine the location and net uplift of the ground surface resulting from the fracture. A laser system called the Ground Elevation Measurement System was developed by UC (patent pending) to measure real-time uplift data during hydraulic fracturing. The system uses a laser and an array of sensors to track the displacement of each point in the array with time.

Factors Affecting Technology Effectiveness

Several factors affect the performance of the hydraulic fracturing technology. These include various site characteristics and the communication between horizontal fractures. These factors, as applied to the SITE demonstrations, are discussed below.

Site Characteristics

Hydraulic fracturing is a permeability-enhancement technique used in conjunction with other soil remediation methods. Therefore, overconsolidated silty clays that have low *in-situ* permeabilities are best suited for the use of hydraulic fracturing. In overconsolidated clays, the horizontal stress is greater than the vertical stress, and this stress condition permits fractures to propagate in a horizontal direction. Fractures that remain horizontal can grow to

significant lengths, thereby enhancing flow in the subsurface.

Hydraulic fracturing is ineffective in normally consolidated clays where the horizontal stress is less than the vertical stress. Demonstrations of hydraulic fracturing in such clays created fractures that were steeply dipping and vented to the surface. Also, the presence of water decreases the efficiency of SVE; hence, the use of hydraulic fracturing to enhance SVE should be limited to unsaturated clays.

Communication Between Horizontal Fractures

Horizontal fractures increase the permeability of soil in their immediate vicinity. However, the permeability of soil between the fractures is not affected unless vertical or inclined fractures are created between the horizontal fractures. Further work at UC is being planned to study this. In SVE applications, changes in soil vacuum (suction head) applied to horizontal fractures may induce communication between the fractures.

Overview of SITE Demonstrations

The SITE demonstrations had the following objectives:

- to establish the viability of creating sand-filled hydraulic fractures in low permeability silty clays,
- to study the factors that affect the performance of the fractures over time,

- to compare the vapor flow rates in wells in fractured and unfractured soils,
- to compare the water flow rates and moisture content in fractured and unfractured soils, and
- to develop information required to estimate the operating costs of the technology.

The Xerox Oak Brook site contained silty clays contaminated with ethylbenzene; 1,1-dichloroethane; trichloroethene; tetrachloroethene; 1,1,1-trichloroethane; toluene; and xylene. Two out of four wells used for two-phase SVE were fractured at depths of 6, 10, and 15 ft bgs. Over a period of 1 yr, the soil vapor flow rates, suction head, and contaminant removal rates were measured and compared for the fractured and unfractured wells. The soil vapor flow was measured with variable area flow meters; the suction head in the vicinity of the wells was measured using pneumatic piezometers; and the contaminant concentration in the soil vapor was measured with a gas chromatograph.

Dayton site contamination included benzene, toluene, ethylbenzene, and xylene (BTEX) and petroleum hydrocarbons. One out of two wells was fractured at depths of 7, 8, 10, and 12 ft bgs. Water containing hydrogen peroxide and nutrients was gravity fed into these wells intermittently for about 6 mos. The site operator was responsible for this activity, and UC was responsible for monitoring the progress of bioremediation near the fractured and unfractured wells. Two rounds of sampling were conducted at locations 5, 10, and 15 ft north of the fractured and unfractured wells after bioremediation was in progress for 1 and 6 mos. Soil samples were obtained and analyzed for moisture content, microbial metabolic activity, number of colony forming units, BTEX, and petroleum hydrocarbons.

The Center Hill Facility tests were conducted in uncontaminated ground during the winter and summer of 1992. Performance of three fractured wells (CHF1, CHF2, and CHF3) was compared with that of two conventional vapor extraction wells (CHC1 and CHC2). Well No. CHF1 intersects hydraulic fractures created at depths of 5 and 10 ft bgs, and Well Nos. CHF2 and CHF3 intersect fractures at a depth of 5 ft bgs. At Well No. CHF2, the fracture intersected the ground surface (vented). Air flow from these wells was measured with variable area flow meters, suction head near the wells was mea-

sured with pneumatic piezometers, and the intensity of rainfall was measured with a rain gauge.

Demonstration Results

The pilot-scale demonstration at the Dayton site and tests at the Center Hill Facility were conducted under the Quality Assurance Project Plan (QAPP), Project Category IV, developed by UC Center Hill. Testing at the Xerox Oak Brook site was conducted by Woodward-Clyde Consultants (WCC) under a QAPP developed by WCC. Center Hill Facility test results and Xerox Oak Brook and Dayton site demonstration results are discussed below.

Center Hill Facility Tests

Parameters measured during the Center Hill Facility tests included air yield, suction head, and rainfall intensity. Air yield was obtained as a function of time and rainfall intensity for three fractured wells and was compared with air yield data from two unfractured wells. Suction head was measured near the fractured and

unfractured wells. The average and maximum yields (in cubic feet per minute [cfm]) and average zone of pneumatic control for the five wells are summarized in Table 1.

The results demonstrate that air yield from fractured wells is one order of magnitude higher than that from unfractured wells. The zone of pneumatic control of the fractured well was 15 to 30 times greater than that for unfractured wells. Rainfall intensity affected the performance of fractured wells, decreasing the yield and increasing the suction head.

Xerox Oak Brook Site Demonstration Results

Vapor discharge from, and suction heads in, two fractured wells (Nos. RW3 and RW4) and one unfractured well (No. RW2) were obtained over a period of 6 mos. The vapor discharge readings (in actual cfm [acfm]) from these wells are summarized in Table 2.

The vapor discharge from fractured wells was about 15 to 30 times greater than

that from the unfractured well. The water recovery rate from the wells fluctuated widely, ranging from 20 to as much as 500 gallons per day. Water recovery rates and vapor discharge rates were inversely related. The cumulative mass of contaminants recovered from fractured wells was consistently one order of magnitude greater than that for the unfractured well. The suction head near the fractured well extended radially about 25 ft, compared with less than 1 ft from the unfractured well. These data correlated well with the radius of fractures in Well Nos. RW3 and RW4.

Dayton Site Demonstration Results

Water flow rates and soil sampling results near a fractured well (SAD2) with fractures at 7, 8, 10, and 12 ft bgs were compared with those from an unfractured well (SAD4). The flow rate of water enriched with hydrogen peroxide and nutrients was about 25 to 40 times greater in the fractured well than in the unfractured

Table 1. Performance of Wells at the Center Hill Facility

Well No.	Average Yield (cfm)	Maximum Yield (cfm)	Average Zone of Pneumatic Control* (ft)
CHF1	3.7	6.1	25 to 30
CHF2	6.7	7.2	20 to 25
CHF3	3.4	4.05	15 to 20
CHC1	0.33	0.38	Less than 1
CHC2	0.59	1.25	Less than 1

*Zone in which the pressure distribution can be controlled by varying the applied suction head.

Table 2. Summary of Well Discharge Readings at Xerox Oak Brook Site

Week No.	Range of Rates	Average Discharge (acfm)	Discharge Percentage in 6 ft bgs Zone	Discharge Percentage in 10 ft bgs Zone	Discharge Percentage in 15 ft bgs Zone
RW2	0.1 - 4.6	1.1	46.3	27.3	23.2
RW3	2.2 - 22.0	14.3	61.2	8.4	30.4
RW4*	27.9 - 42.7	34.2	36.0	41.0	23.0
RW4 †	17.1 - 29.7	22.6	not applicable	not available	not available

*The 6-ft-deep fracture at Well No. RW4 vented to the surface. Data for this well include the discharge average when suction was applied to all three of the fractures.

†Well discharge average when suction was applied to the 10- and 15-ft-deep fractures only. Hence, well discharge was smaller than when suction was applied to all three of the fractures.

well (see Figure 3). This increased flow resulted in doubling the moisture content near the fractured well. The demonstration did not provide reliable quantitative data on contaminant removal rates at the site.

Costs

Economic data obtained from the SITE demonstrations were analyzed to estimate the cost of using this hydraulic fracturing technology at a hazardous waste site remediation. Twelve cost categories were examined, including capital costs, labor costs, and supplies and consumables costs.

The capital equipment costs include costs for an equipment trailer on which the slurry mixer, pumps, tanks, and hoses are mounted; a fracturing lance with well-head assembly; pressure transducer and display; and uplift survey instruments. The capital equipment cost was \$92,900. A capital equipment daily rental cost, assuming 30 rentals/yr and a depreciation life of 3 yrs, was \$1,000. A crew of four to

five can operate the fracturing and monitoring equipment. Labor costs were estimated to be about \$2,000/day. Supplies and consumables include sand, guar gum gel, enzyme, and diesel or gasoline for operating the pumps. The cost for supplies and consumables was about \$1,000/day. The daily cost for creating about four to six fractures was about \$5,700 and included site preparation (\$1,000) and cost of installing pneumatic piezometers (\$700) near the fractures. Hence, the cost per fracture can vary from about \$950 to \$1,425.

Conclusions

The tests conducted at the Center Hill Facility and the pilot-scale demonstrations completed at the Xerox Oak Brook and Dayton sites lead to the conclusions presented below.

1. Sand-filled hydraulic fractures, up to 1 in. thick and 25 ft in radius, can be created in overconsolidated, low permeability silty clays.

2. The fractures remained effective for a period of more than 1 yr. Rainfall decreased vapor yield and increased suction head of fractured wells. Unfractured wells were not affected by rainfall.
3. Fractured wells yielded vapor flow rates 15 to 30 times greater than did unfractured wells. This increased flow was obtained from a distance of 25 ft away from the fractured well.
4. The water flow was about 25 to 40 times greater in a fractured well than in an unfractured well.
5. The cost of creating a fracture can vary from about \$950 to \$1,425.

The technology demonstrations have established the increased permeability in silty clays resulting from hydraulic fractures and the radius of influence of these fractures. Further enhancements of *in-situ* permeability can be achieved if communication can be created between horizontal fractures.

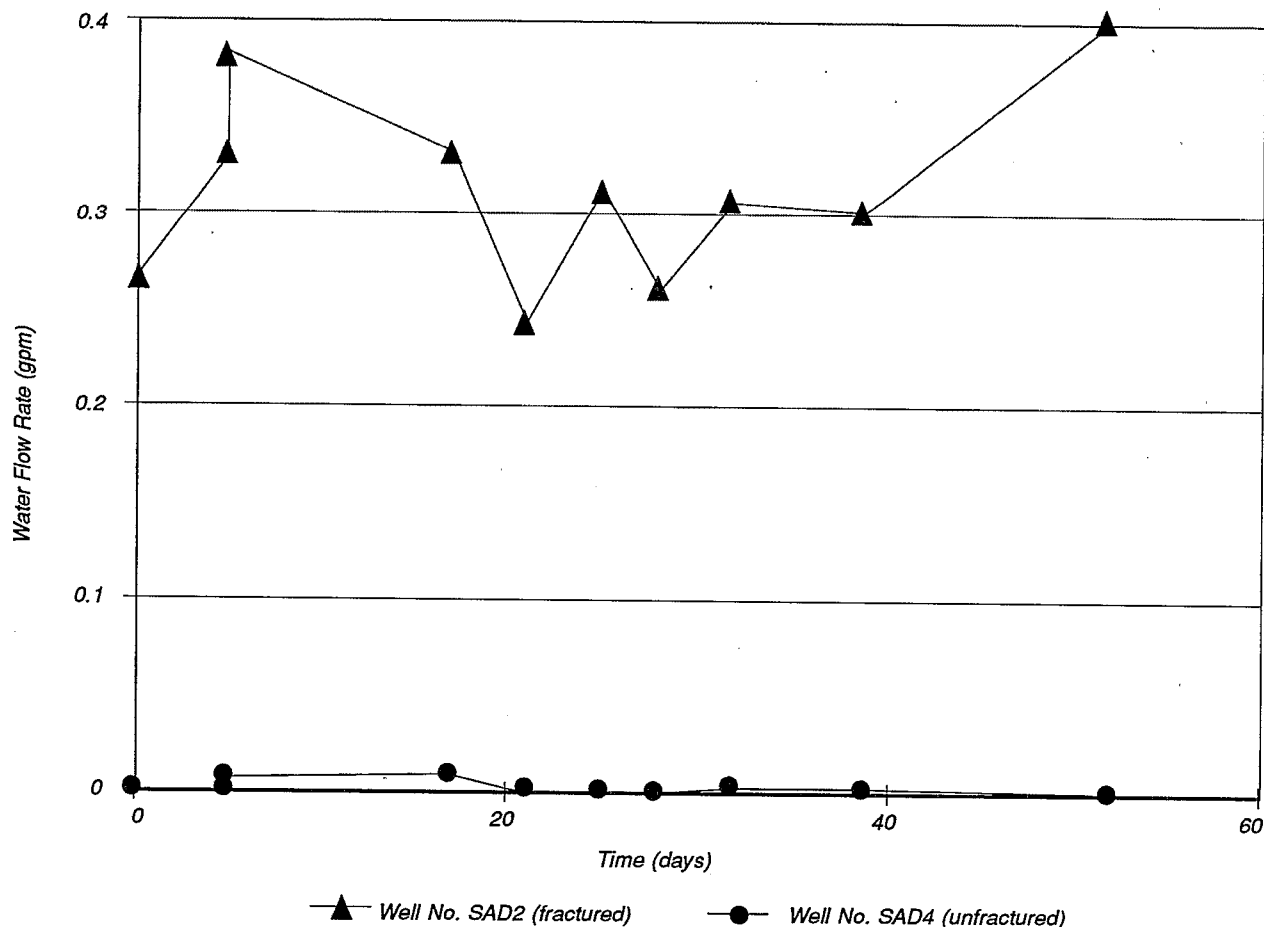
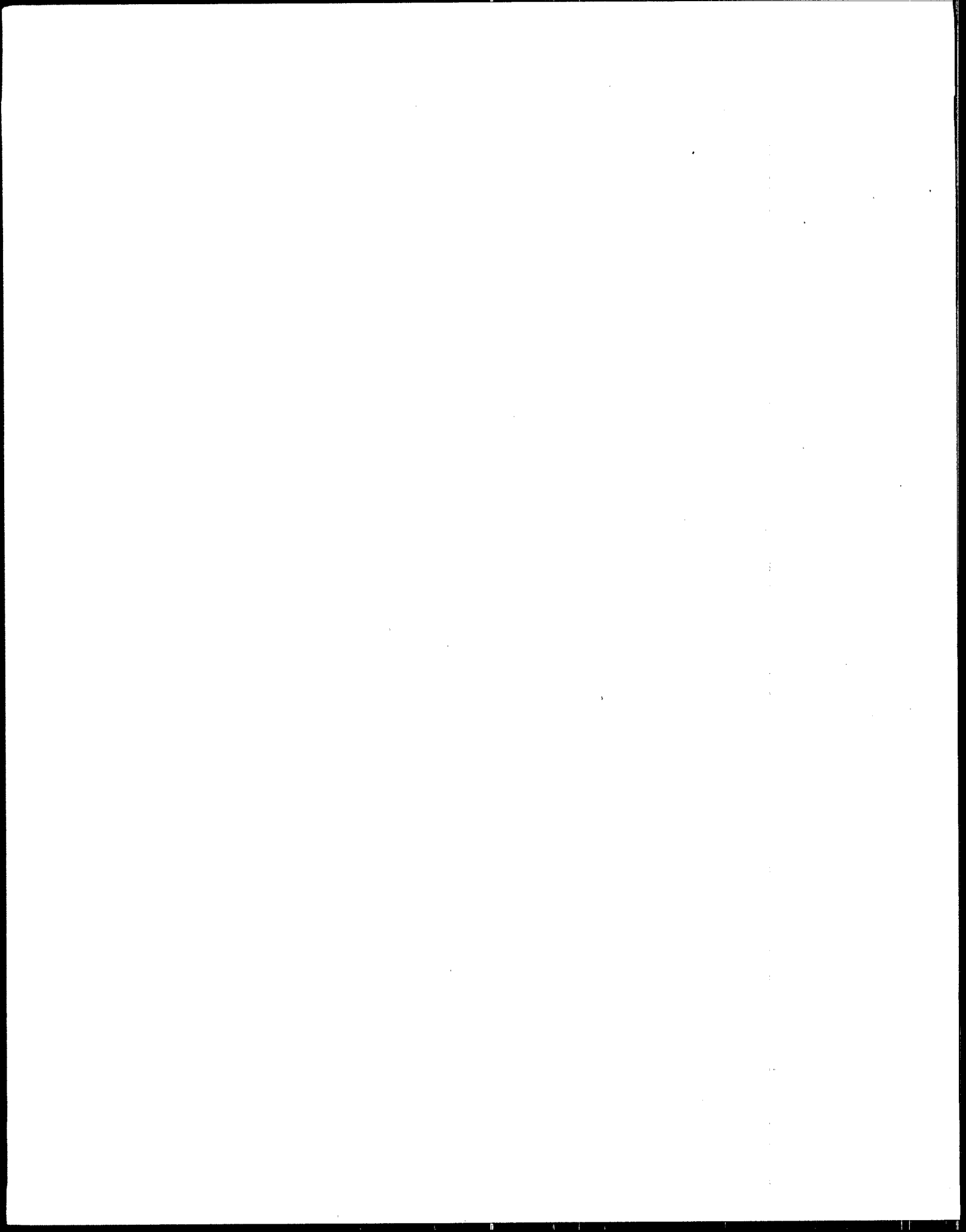
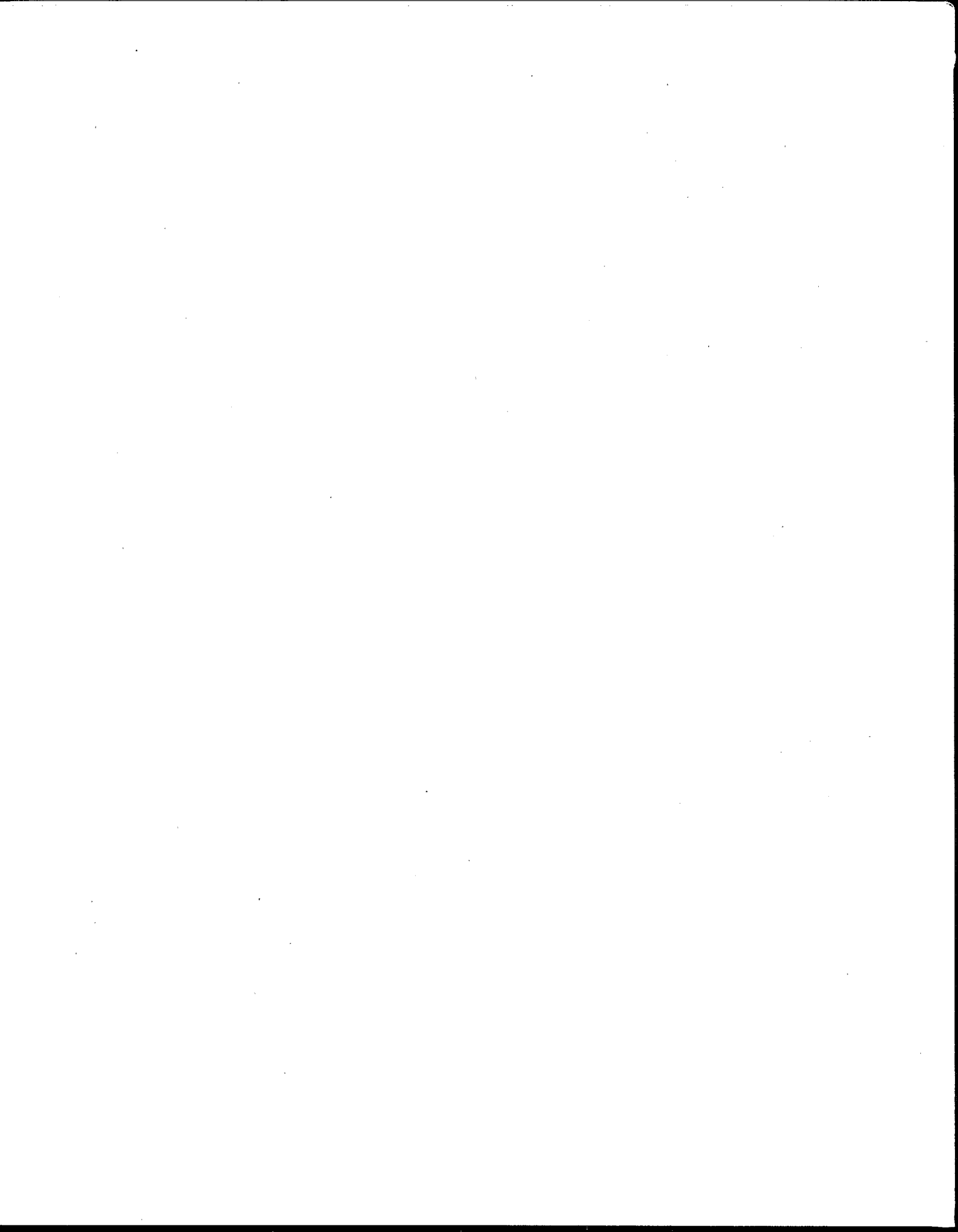


Figure 3. Flow volumes of injected water in wells no. SAD2 and SAD4.





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The complete report, entitled "Hydraulic Fracturing Technology —Technology Evaluation and Applications Analysis Reports," (Order No. PB94 -100 161/AS; Cost: \$27.00, subject to change), will be available from:

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